ASPECTS OF TRANSITION IN TURBOMACHINES*

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ABSTRACT

This talk provides a description several types of transition encountered in turbomachines. It is based largely on personal experience of the detection of transition in turbomachines. Examples are taken from axial compressors, axial turbines and radial turbines. The illustrations are concerned with transition in steady and unsteady boundary layers that develop under the influence of two-dimensional and three-dimensional flow fields.

Studies of transition in turbomachines are usually compromised since they are difficult to conduct in realistic environments. The physical size of the airfoils, the time-scales of phenomena, problems of accessibility and cost all conspire against the experimentalist. Yet, transition is known to be affected by many parameters and several causes may simultaneously compete to bring about transition in any one given situation in a turbomachine. In addition, the same apparent cause can give rise to different modes. Uncertainty therefore surrounds the measurement of transition onset and the measurement of the transition zone. This undoubtedly hinders the continuing search for improved turbomachine designs. Furthermore, it is argued that while less complex simulations must continue to be used to further understanding and knowledge of transition in turbomachines, experiments must be conducted in realistic environments. Such studies should include investigations of the nature of transition and of the various causes. Once the nature of the processes is better understood, specific problems regarding the origin of the transitional flow and its development may be addressed with confidence. One of the most important outcomes of this research should be the implementation of appropriate physical models of transition in current and future numerical calculation schemes.

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GENERAL OBSERVATIONS

Studies of transition in turbomachines compromised since

- difficult to conduct in realistic environments
- often limited to less complex simulations

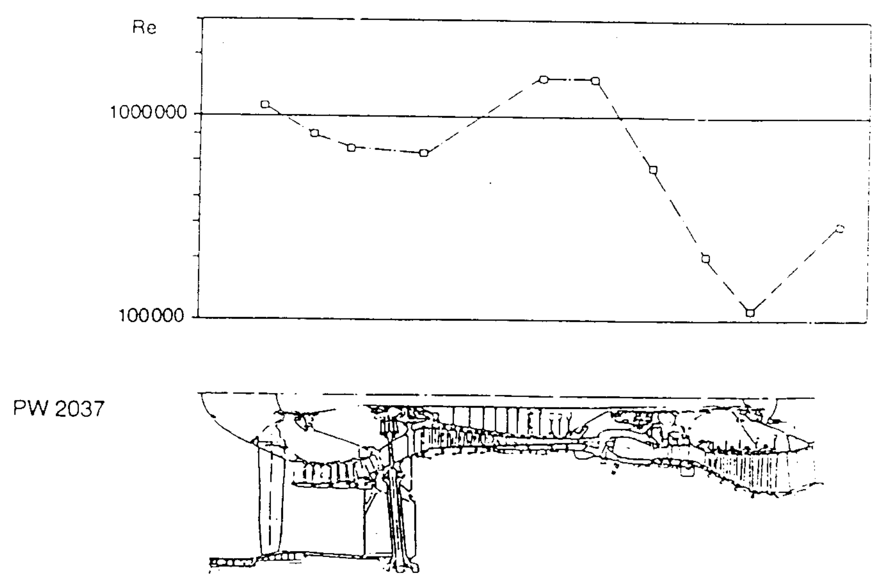
In turbomachines, transition

- influenced by many parameters
- may be due to one or more competing causes in a given situation

Uncertainty

- surrounds predictions of transition onset and development of transition zone
- limits improvements in technology

REYNOLDS NUMBERS IN AXIAL TURBOMACHINES



VARIATION OF REYNOLDS NUMBER IN BY-PASS ENGINE AT CRUISE
(HOURMOUZIADIS, 1989)

OBJECTIVES

- Introduce particular aspects of turbomachine transition
- Highlight some of the problems by use of examples
- Set scene for remainder of session

MOTIVATION

Problems

- Where does transition/separation occur?
- How can we model these phenomena?

Answers affect

- design of bladerow
- efficiency
- heat transfer & cooling requirements

INFLUENCES ON TRANSITION IN TURBOMACHINES

- free stream turbulence (magnitude/scale/homogeneity)
- pressure gradients
- fast (e.g., shocks) and slow (e.g., wakes) fluctuations of free stream pressure, temperature, velocity, turbulence
- separation
- film cooling
- laminarization
- rotation (Coriolis & centripetal accelerations)
- curvature
- quasi 3D effects - divergence/convergence of stream-lines
- 3-D effects - e.g., skew

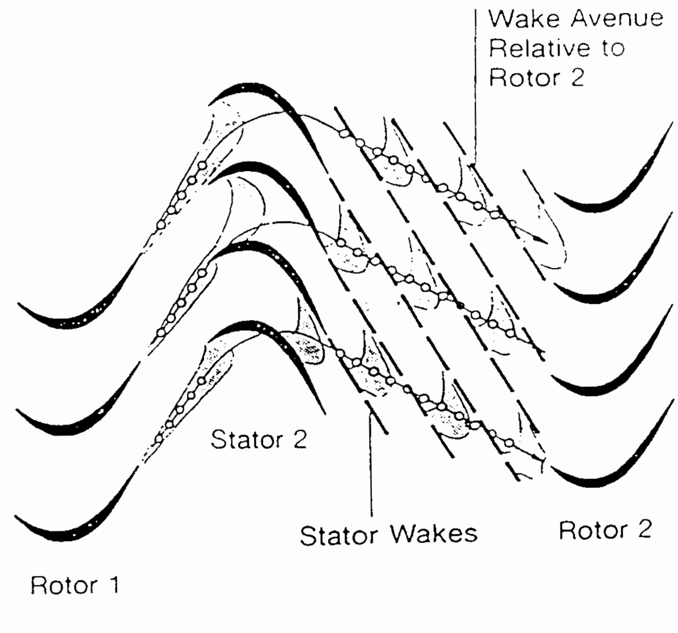
WAKE INDUCED TRANSITION IN TURBOMACHINES

Wakes represent perturbations in

- Velocity
- Turbulence (typ. 3-5% max)
- Pressure ......etc.

Wakes give rise to

- premature transition

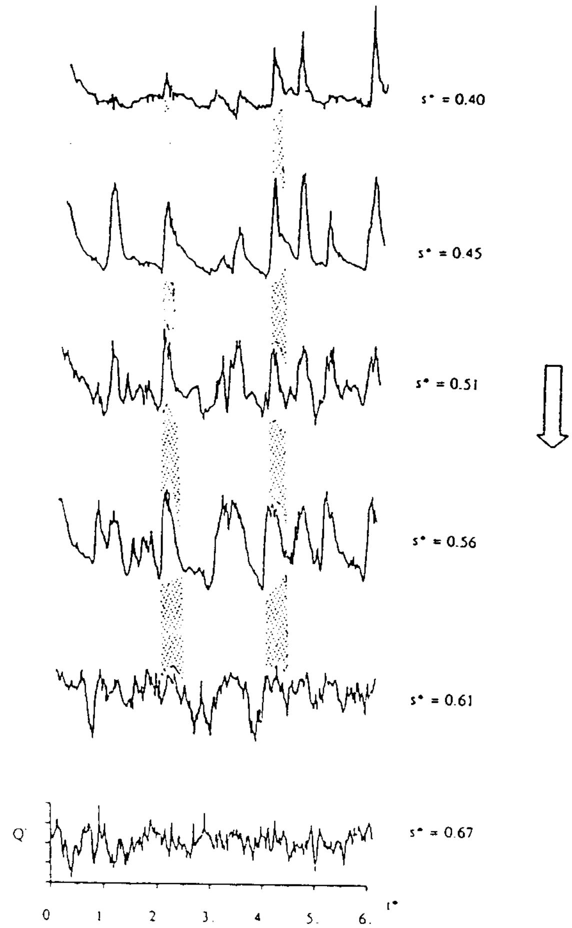


WAKES IN MULTISTAGE LP TURBINE (ARNDT)

Affects can extend beyond next bladerow

WAKE INDUCED TRANSITION IN WHITTLE LAB AXIAL TURBINE

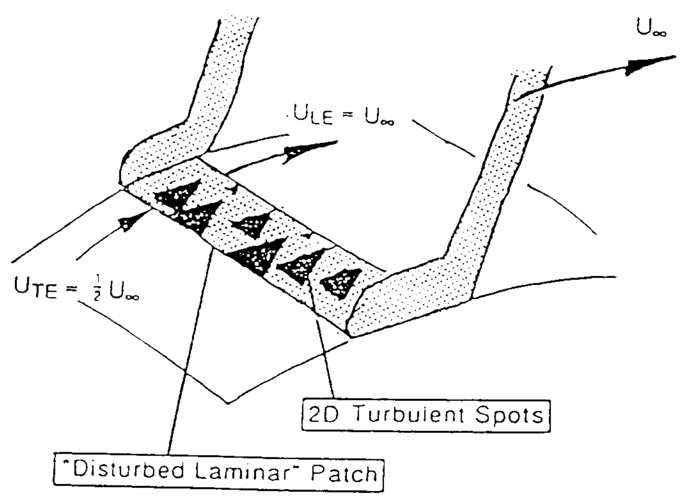
- Turbulent 'events' more probable when wake present
- $U_{LE} \approx 0.88$xfree-stream
- $U_{TE} \approx 0.50$xfree-stream
- Like turbulent spots - but are they?



SURFACE-MOUNTED HOT-FILM SIGNALS FROM ROTOR SUCTION SURFACE (ADDISON, 1990)

SIMPLE DESCRIPTION OF 2-D WAKE-INDUCED TRANSITION

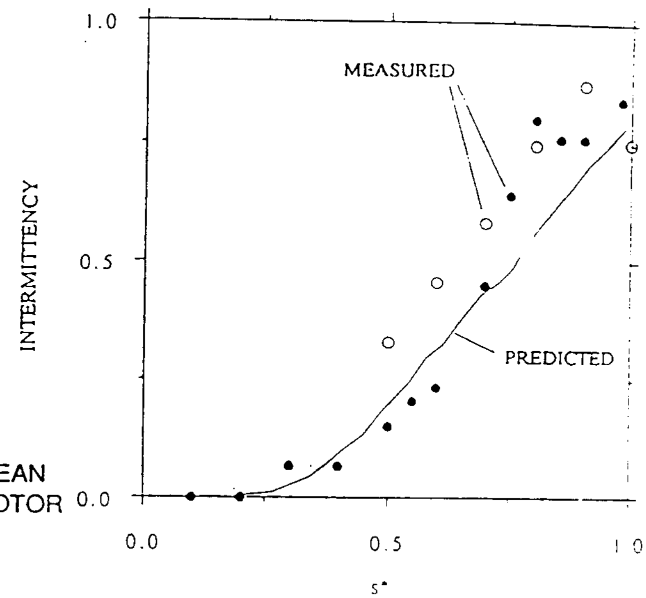
- periodic
- caused by turbulence(?) in wakes
- similar to steady transition



UNSTEADY 2-D TRANSITION MODEL

DATA FROM THE WHITTLE LAB. AXIAL TURBINE

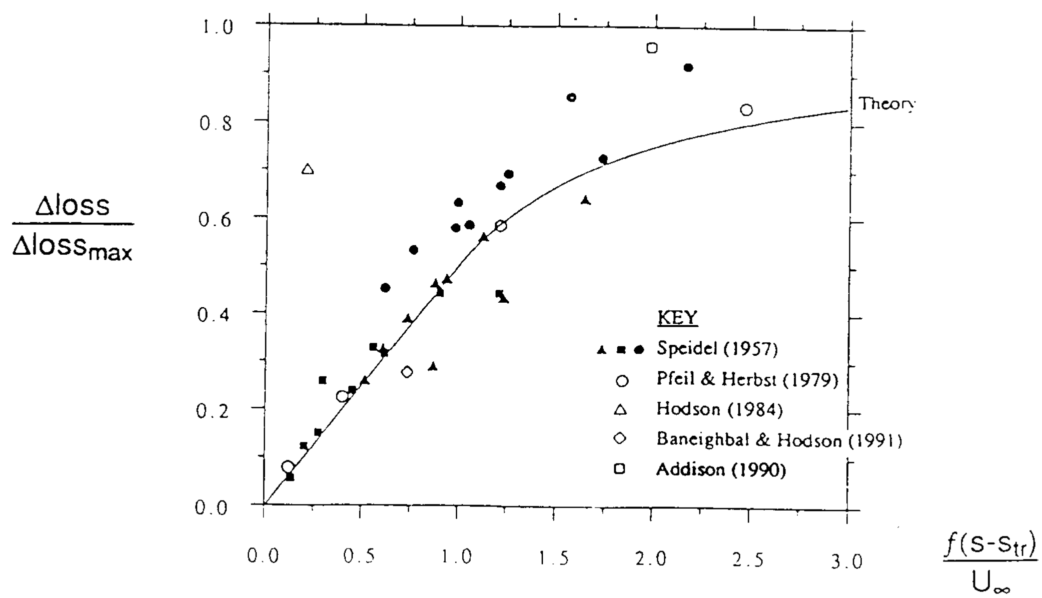
- Single stage
- Re = 3.5×10^5
- $\frac{f \Delta s}{U} = 0.86$
- Onset based on experimental observation
- Spot Production: $\frac{n \sigma \theta_{tr}^3}{\upsilon} = \text{const.}$



PREDICTED AND MEASURED TIME-MEAN INTERMITTENCY $\bar{\gamma}$(S) FOR TURBINE ROTOR MID-SPAN SUCTION SURFACE (HODSON ET AL 1992)

EFFECT OF WAKE-PASSING FREQUENCY ON LOSS

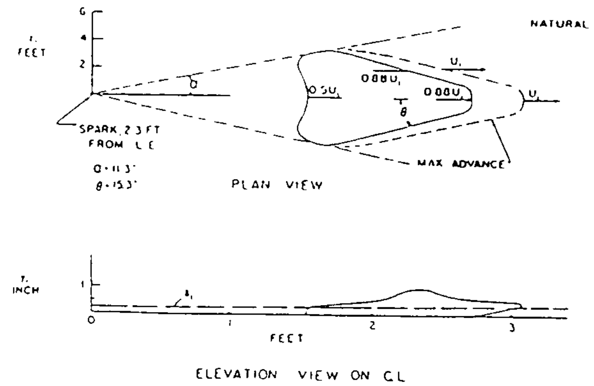
Assume wake-affected zone is turbulent



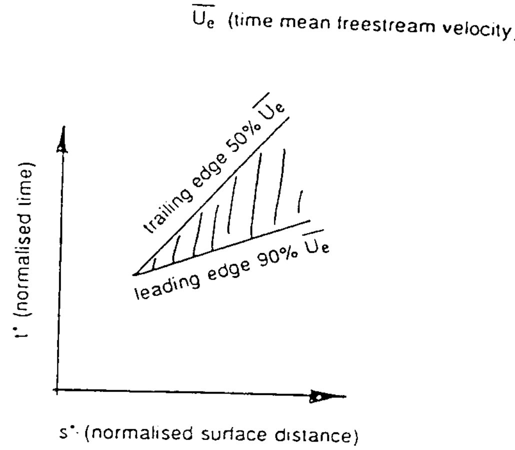
EFFECTS OF UNSTEADINESS ON PROFILE LOSS SHOWING COMPARISON BETWEEN SIMPLE MODEL AND EXPERIMENTS (HODSON, 1989)

S-T DIAGRAM FOR WAKE-INDUCED TRANSITION

Analogy with turbulent spot



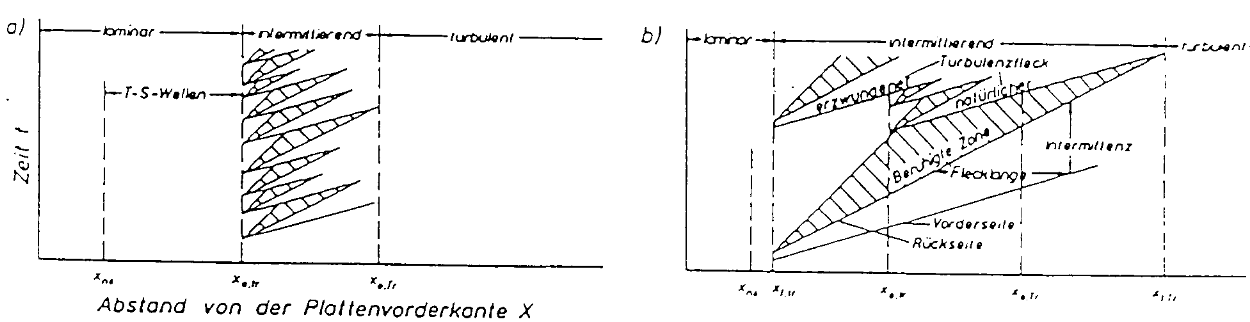
GEOMETRY AND GROWTH OF SPOT



S-T DIAGRAM OF SPOT

EXTENDED TRANSITION ZONES

Calmed region behind turbulent 'events' can extend transition zone (Schubauer & Klebanoff, 1955)



SCHEMATIC INTERPRETATION OF TRANSITION ON A FLAT PLATE: (A) NATURAL TRANSITION; (B) WAKE-INDUCED AND NATURAL TRANSITION (PFEIL, HERBST AND SCHRÖDER, 1982)

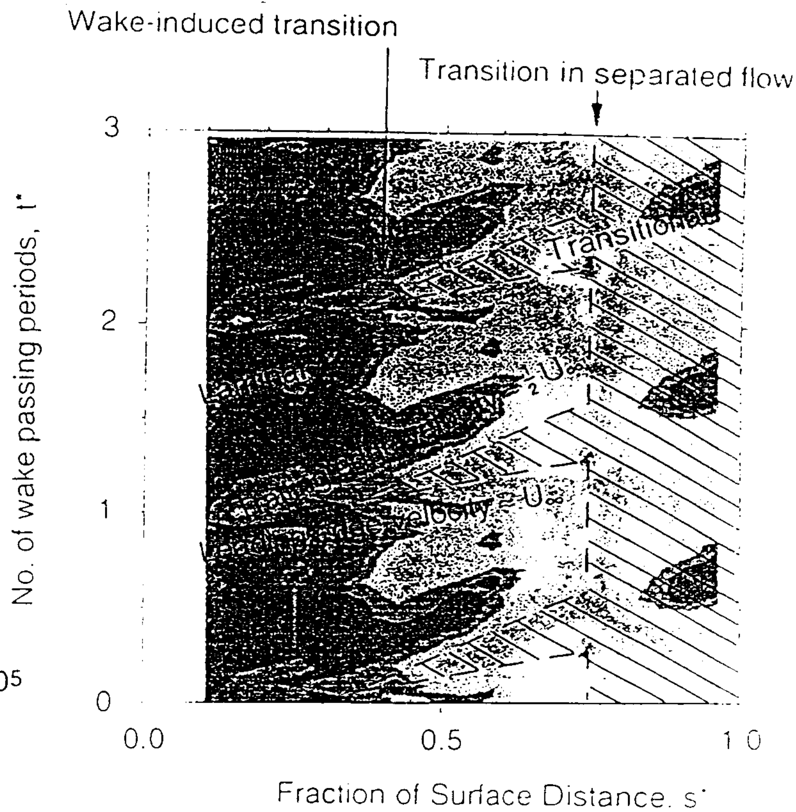
MULTI-MODE TRANSITION IN AN LP TURBINE

If steady flow transition occurred at 0.4s

- correlations predict 50% intermittency γ at 0.75s

For wake-affected flow,

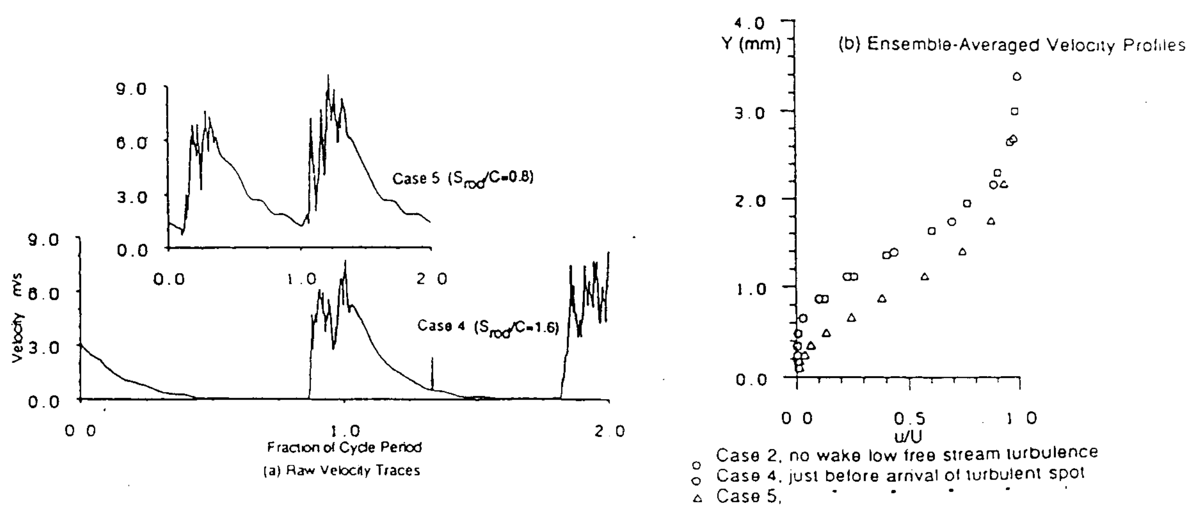
- $\gamma_{max} \leq$ steady flow value
- limits calming effect
- separation possible when not instantaneously turbulent



ENSEMBLE-SKEW MEASURED BY SURFACE HOT-FILMS, RE = 1.3X10^5 (HODSON ET AL, 1993)

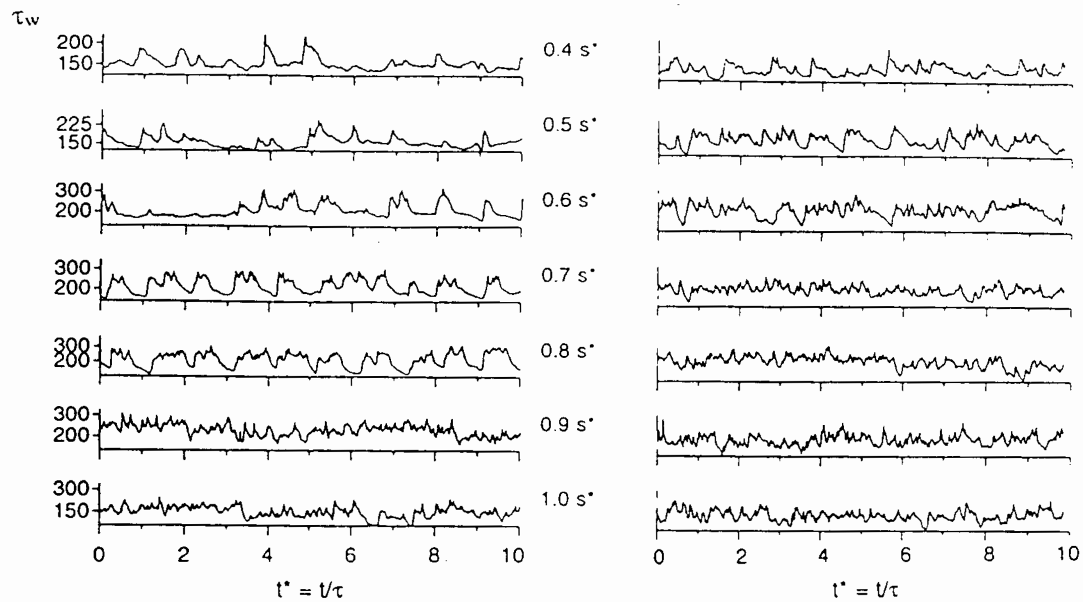
DELAYED SEPARATION/TRANSITION

Calmed region behind turbulent 'events' delays separation/transition



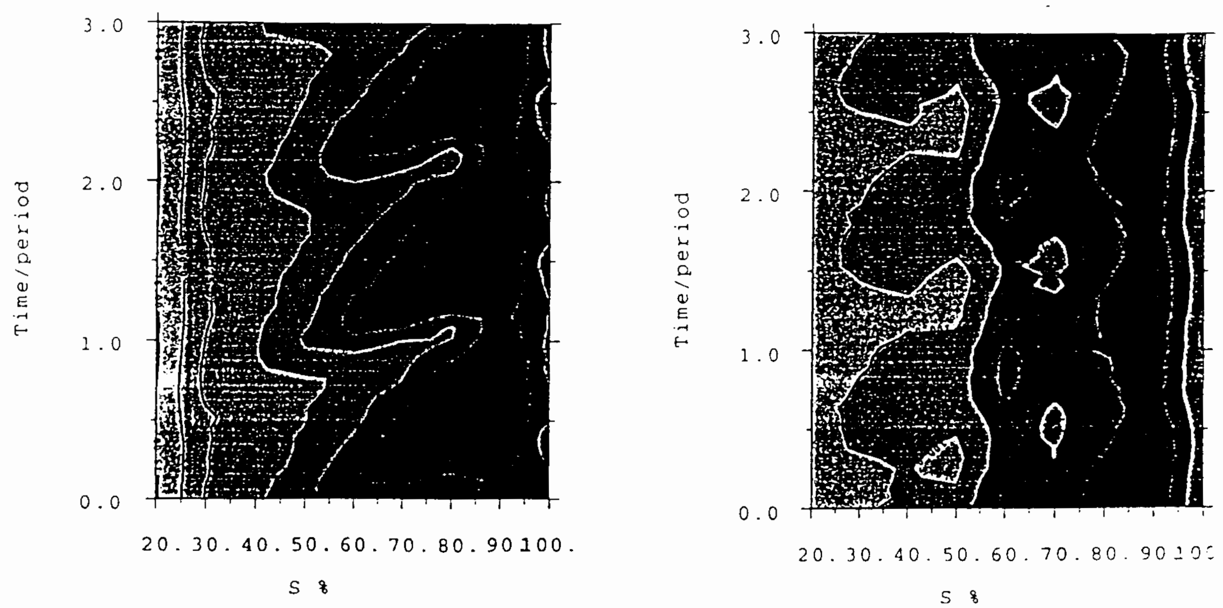
WAKE-INDUCED TRANSITION IN A COMPRESSOR CASCADE (A) INSTANTANEOUS VELOCITIES NEAR SUCTION SURFACE AND (B) ENSEMBLE-AVERAGED VELOCITY PROFILES FOR DIFFERENT UPSTREAM WAKE PITCHES (DONG & CUMPSTY, 1989)

MULTI-MODE TRANSITION IN 2-STAGE TURBINE



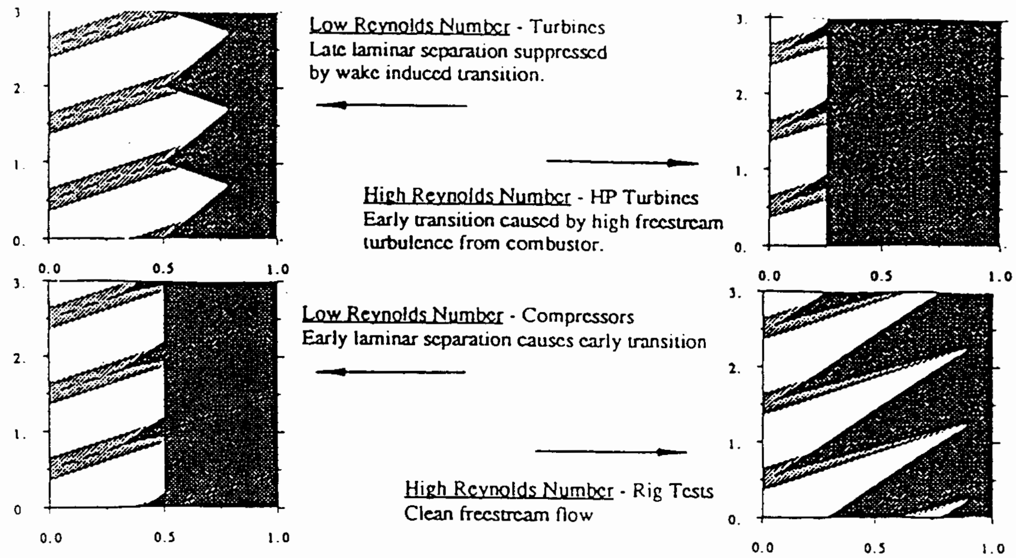
HOT-FILM OUTPUT SIGNALS ON TURBINE ROTOR MID-SPAN SUCTION SURFACE
(A) 1ST STAGE - LOW TU BETWEEN WAKES (FROM HODSON ET AL 1993)
(B) 2ND STAGE: DISTURBANCES PRESENT BETWEEN WAKES

MULTI-MODE TRANSITION IN 2-STAGE TURBINE



DISTANCE TIME-DIAGRAMS OF ENSEMBLE-MEAN WALL SHEAR STRESS ON TURBINE ROTOR MID-SPAN SUCTION SURFACE
(A) 1ST STAGE - LOW TU BETWEEN WAKES (FROM HODSON ET AL 1993)
(B) 2ND STAGE: DISTURBANCES PRESENT BETWEEN WAKES

SUMMARY OF WAKE-INDUCED TRANSITION



S-T DIAGRAMS SHOWING START OF TRANSITION TRENDS FOR LOW AND HIGH REYNOLD NUMBER FLOWS IN TURBINES AND COMPRESSORS (ADDISON, 1990)

WAKE-INDUCED TRANSITION

What really causes it - turbulence, velocity, pressure fluctuations ?

Where do spots/turbulent 'events' really form/how is this affected by changes in free-stream?

Why do some see wake-affected intermittent flow while others see turbulent flow?

What are the implications of existence of calmed region
(a) at rear of spots inside wake-affected zone?
(b) at rear of fully turbulent wake-affected zones?

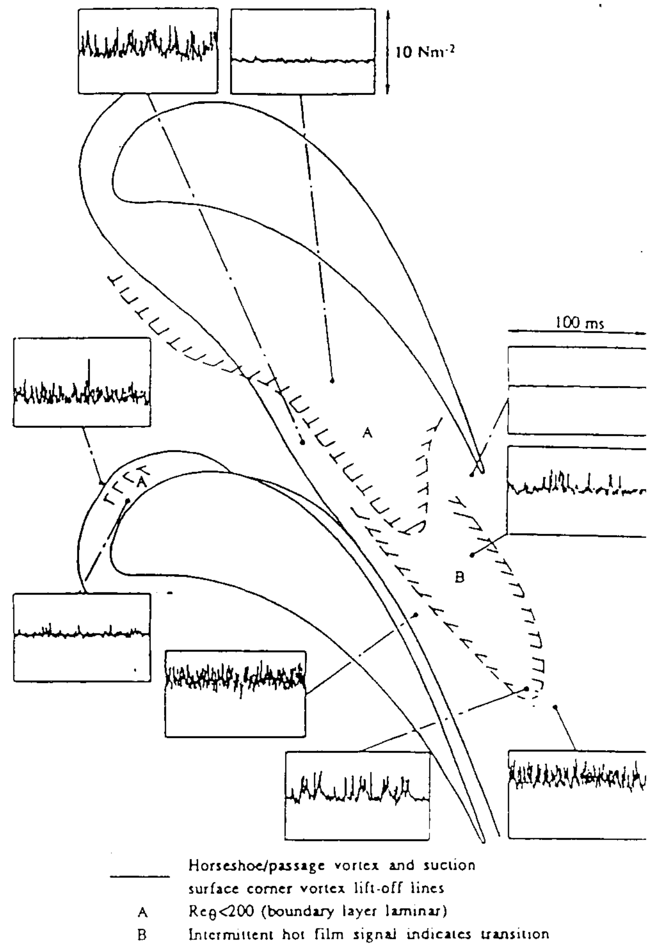
What happens when wakes traverse a separation zone/how do free-stream conditions affect transition in separated flows?

ENDWALL TRANSITION IN AXIAL FLOW TURBINES

Secondary flow leads to

- 3-d boundary layers
- new, accelerating laminar flow behind lift-off line
- intermittent flow in rear of blade passage

How do we model 3-D transition?



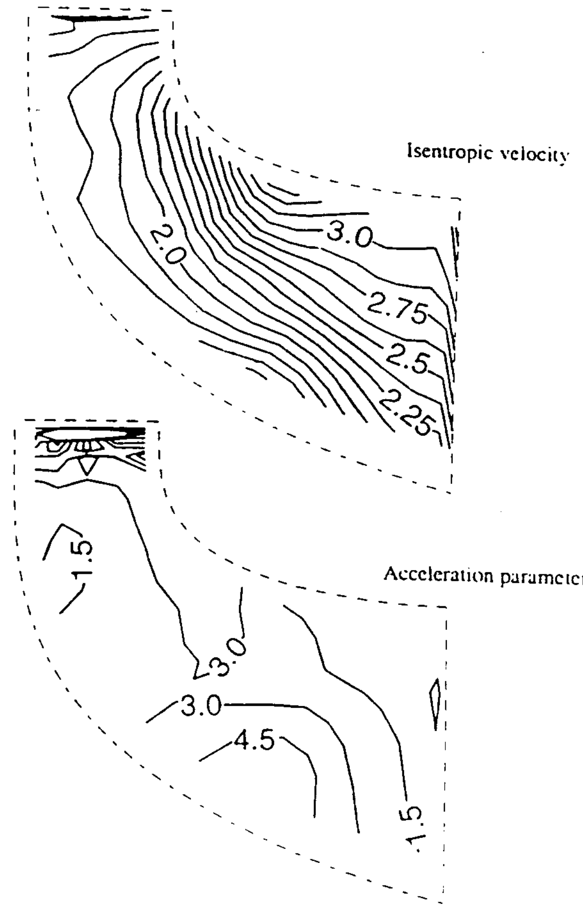
HOT-FILM OUTPUT SIGNALS FROM ENDWALL OF A 2-D TURBINE CASCADE (HARRISON, 1989)

RADIAL INFLOW TURBINES

- significant skew/secondary flows on blade surfaces
- $Re_s \approx 10^6$
- Continuous acceleration over much of surface
- High values of acceleration parameter

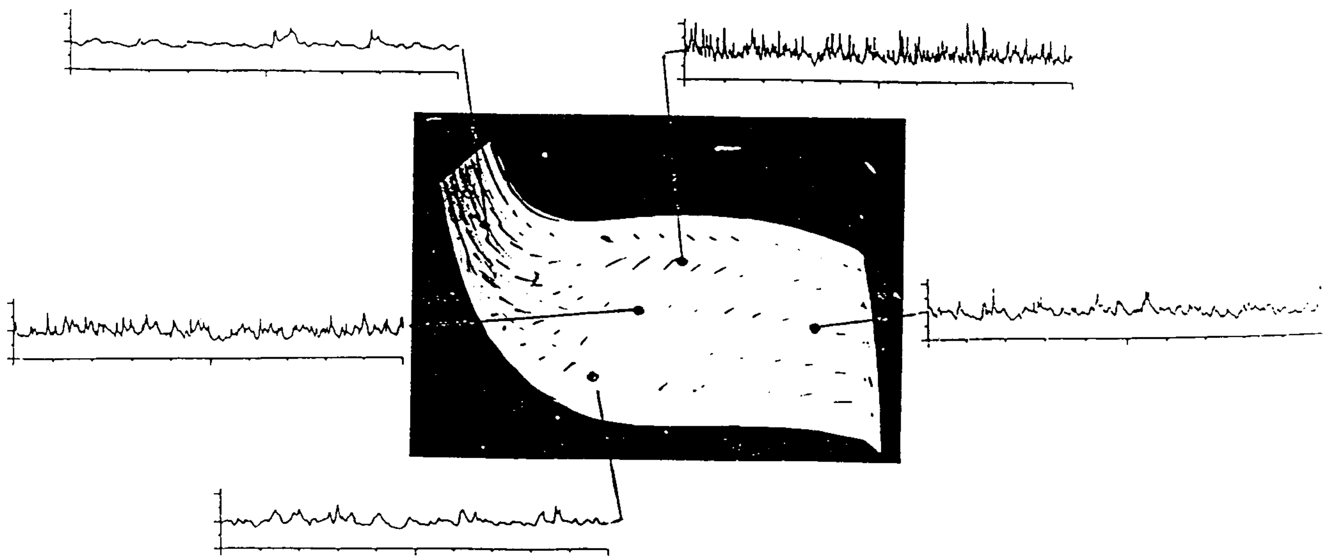
$$k = \frac{\nu}{w^2}\nabla(w)$$

especially in secondary flow direction



CONTOURS OF VELOCITY $W/W_{RADIAL,IN}$ AND ACCELERATION $|K| \times 10^6$ ON SUCTION SURFACE OF ROTOR OF A RADIAL INFLOW TURBINE (HUNTSMAN & HODSON, 1993)

RADIAL INFLOW TURBINES



HOT-FILM OUTPUT SIGNALS AND SURFACE FLOW VISUALISATION FROM SUCTION SURFACE OF ROTOR OF A RADIAL INFLOW TURBINE (HUNTSMAN & HODSON, 1993)

INVESTIGATION OF TURBULENT SPOT FORMATION & TRANSITION USING THERMOCHROMIC LIQUID CRYSTALS

PROBLEMS

Existing database insufficient to answer important questions

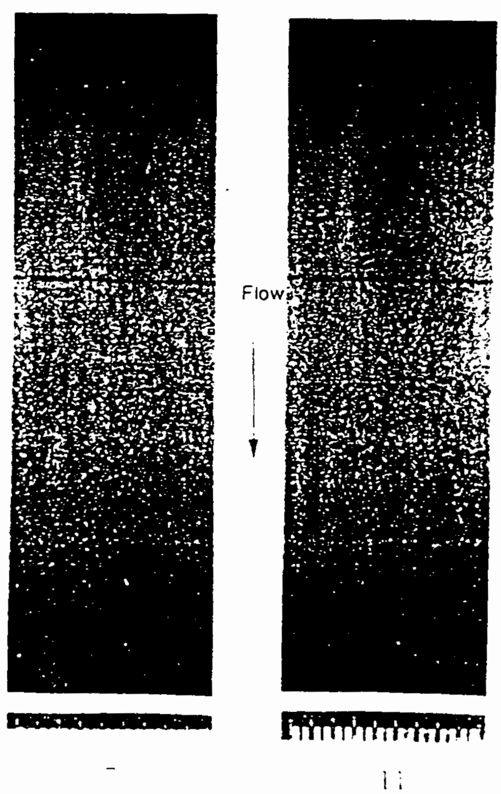
- Where and when do turbulent spots form?
- How is their formation and growth affected by free-stream conditions?

SOLUTION

- Investigate development of transitional flow using fast-response instrumentation with full surface coverage, i.e. thermochromic liquid crystals

ADVERTISEMENT

- A opportunity exists for a Post-Doc to work on this project at Oxford then Cambridge University



HOT FILM OUTPUT TRACES

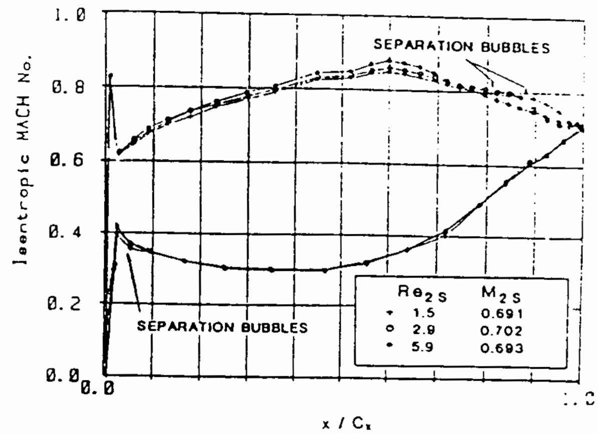
SEPARATION/TRANSITION/LAMINARIZATION

Sharp leading edges can cause separation on both surfaces near l.e.

Flow separates at low Re

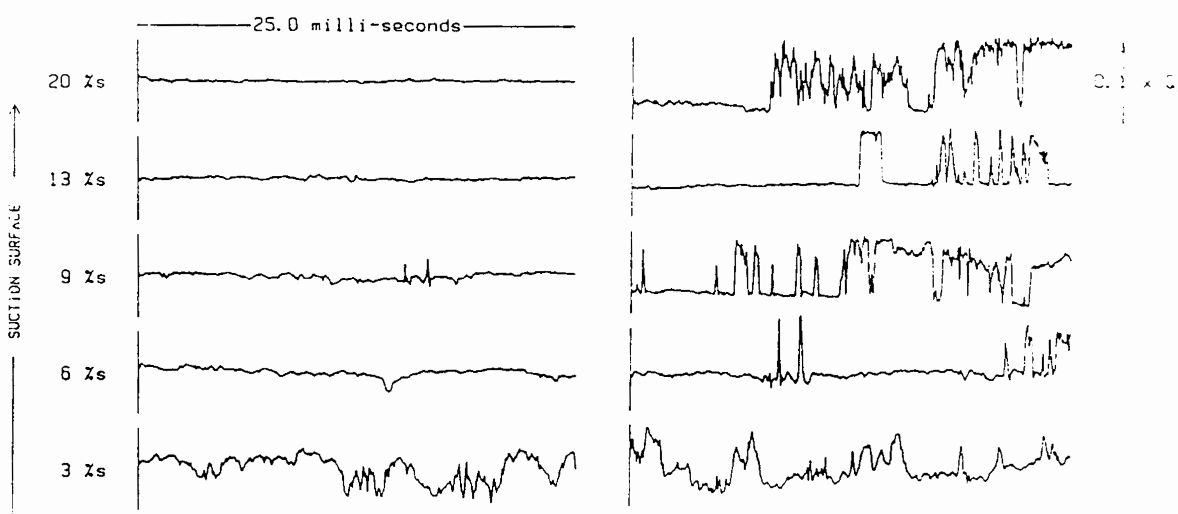
Questions:

- where does it reattach?
- why does it reattach - acceleration/transition?
- what happens after reattachment?



MACH NUMBERS AROUND AN LP TURBINE BLADE (HODSON, 1985)

EFFECT OF PRESSURE GRADIENT/REYNOLDS NUMBER ON SEPARATION/TRANSITION/LAMINARIZATION



(A) RE ≈ 3X10⁵ (B) RE ≈ 9X10⁵

SURFACE-MOUNTED HOT-FILM OUTPUT SIGNALS FROM AROUND LEADING EDGE OF AN LP TURBINE BLADE, TU=0.5% (HODSON, 1985):

MODELLING TRANSITION IN TURBOMACHINES

Various approaches used in design

- Integral B.L. codes
- Differential codes + algebraic transition/turbulence models
- Differential codes + differential transition/turbulence models

B.L. codes may be coupled to inviscid solvers or stand-alone

Differential codes based on 2-D or 3-D forms of Navier-Stokes or B.L. equations

Transition is modelled using either intermittency or turbulence models

INTERMITTENCY

$$\gamma(P) = 1 - \exp\left[-\int_V g(P_0)\, dV_0\right]$$

- applicable to all flows providing spot production rate $g(P_0)$ and dependence volume V are known - these have never been measured
- 'natural companion' to 2-D integral solutions (linear combination)
- difficult to use correctly with algebraic turbulence models (profile switching)
- exclude effect of changing free-stream conditions - existing correlations based on conditions up to start of transition only

How do we prescribe spot production rate $g(P_0)$ and dependence volume V for general problems (unsteady, 3-D, variable free-stream conditions .....)?

TRANSITION VIA TURBULENCE MODELS

Solutions (e.g., via k-ε equations)

- rely on same boundary layer test data as other correlations for validation
- can account for effects of changing free-stream conditions
- can give development of free-stream turbulence etc.
- not limited to boundary layers
- computationally efficient when y^+ hard to find, e.g. unstructured 3-D codes
- do not contain all physics - e.g. influence zones in unsteady flow, intermittent separation

FINAL REMARKS (1)

We know

- some parameters are significant (e.g., pressure grad., Tu intensity, history)
- some parameters may be significant (e.g., curvature, Tu scale, skew)

In many cases, we do not know

- the nature of transition
- the magnitude/significance of the various parameters

We need

- more systematic studies of transition - <u>must be applicable to turbomachines</u>

FINAL REMARKS (2)

Various numerical approaches/codes used in design

Whatever the approach, majority of transition models

- rely on same experiments for validation/correlation

To be effective in design, we need

- integral 2-D steady B.L. methods .... 3-D unsteady N-S codes
- consistent hierarchical models of transition based on physics